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OPINION

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The overlooked spatial dimension of climate-smart agriculture

Reinhard Prestele[1] | Peter H. Verburg[1,2]

[1]Environmental Geography Group, Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

[2]Swiss Federal Research Institute WSL, Birmensdorf, Switzerland

Correspondence and present address
Reinhard Prestele, Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology, Kreuzeckbahnstr. 19, 82467 Garmisch-Partenkirchen, Germany.
Email: reinhard.prestele@kit.edu

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Abstract

Climate-smart agriculture (CSA) and sustainable intensification (SI) are widely claimed to be high-potential solutions to address the interlinked challenges of food security and climate change. Operationalization of these promising concepts is still lacking and potential trade-offs are often not considered in the current continental- to global-scale assessments. Here we discuss the effect of spatial variability in the context of the implementation of climate-smart practices on two central indicators, namely yield development and carbon sequestration, considering biophysical limitations of suggested benefits, socioeconomic and institutional barriers to adoption, and feedback mechanisms across scales. We substantiate our arguments by an illustrative analysis using the example of a hypothetical large-scale adoption of conservation agriculture (CA) in sub-Saharan Africa. We argue that, up to now, large-scale assessments widely neglect the spatially variable effects of climate-smart practices, leading to inflated statements about co-benefits of agricultural production and climate change mitigation potentials. There is an urgent need to account for spatial variability in assessments of climate-smart practices and target those locations where synergies in land functions can be maximized in order to meet the global targets. Therefore, we call for more attention toward spatial planning and landscape optimization approaches in the operationalization of CSA and SI to navigate potential trade-offs.

KEYWORDS

conservation agriculture, ecosystem services, food security, sub-Saharan Africa, sustainable intensification, trade-off analysis

1 | INTRODUCTION

Ensuring global food security, while limiting the impacts of climate change will pose huge challenges to humanity within the coming decades (Godfray et al., 2010; Peters et al., 2013). Past increases in agricultural production often came at the cost of the environment and ecosystem services provided to society (Power, 2010), yet similar growth rates of agricultural yields are unlikely to be achieved in future (Ray, Mueller, West, & Foley, 2013). Hence, alternatives to the continuing expansion of cropland and conventional intensification are urgently required to ensure future food security and sustain earth system functioning (Pretty et al., 2018; Tilman, Balzer, Hill, & Befort, 2011).

Sustainable intensification (SI) of agriculture has been suggested as a high-potential solution to resolve competing claims on limited land resources (Garnett et al., 2013; Pretty, 2008; Rockström et al., 2017). SI summarizes agricultural management strategies that are supposed to increase agricultural production while minimizing the environmental costs. In the context of the climate change debate, SI widely overlaps with the concept of climate-smart agriculture (CSA; Campbell, Thornton, Zougmoré, van Asten, & Lipper, 2014). CSA includes three central promises: (a) the increase of agricultural production on present-day agricultural areas (=intensification) (Garnett et al., 2013); (b) the increasing resilience of agricultural systems and farming households toward climate change (=climate change adaptation) (Lipper et al., 2014); and (c) the reduction of agricultural greenhouse gas emissions and enhancement of soil carbon sinks (=climate change mitigation) (Smith et al., 2008). The CSA concept is thereby not limited to purely technological innovations, but also includes changes at the policy and institutional levels (Lipper et al., 2014) and has a strong context-specific component, both in location and time (Bell et al., 2018).

However, while the definition of the CSA concept emphasizes the context specificity (FAO, 2010), global assessments of future food security and climate change mitigation through agricultural transformation have paid surprisingly little attention to the spatial variability in benefits of climate smart management strategies. Instead, the spatial variability in social–ecological conditions determines if, and to what extent, agricultural systems can be considered climate smart and a viable option with overall positive effects on the global food and climate systems. For example, to balance climate and food production objectives at the local scale, decreases in yields may be unavoidable and cause land clearing elsewhere to compensate for these losses. Similarly, local increases in yields may induce expansion of agricultural land as the revenue for the farmer will be larger and consumer prices lower (Lambin & Meyfroidt, 2011). However, only few publications started to take this variability and feedbacks into account and, hence, only few publications consider the limitations to apply climate-smart interventions at the continental or global scale (e.g., Rasmussen et al., 2018; Scherer, Verburg, & Schulp, 2018).

While balancing the context-specific trade-offs is a core component of both SI and CSA concepts (Garnett et al., 2013; Godfray & Garnett, 2014; Lipper et al., 2014; Pretty, 2008; Rockström et al., 2017; Smith, 2016), the spatial variability of outcomes is still treated as a sideline in global assessments and the main message of high hopes in the global potential of climate-smart interventions is hardly nuanced. Global assessments too often assume uniform effects on all cropland (e.g., for soil carbon sequestration; Smith et al., 2008) or include implicit assumptions about potential yield gains in present-day cropping systems (e.g., Griscom et al., 2017). To date, hardly any attempts are made to identify and quantify the local-scale co-benefits and trade-offs, that is, locations where climate-smart management either increases or decreases the benefits from other ecosystem services such as soil carbon sequestration, which eventually would allow more realistic estimates of net impacts at the larger scale.

While not arguing against the benefits of CSA as compared to conventional intensification per se, in our view the dimensions of location and scale are key in the assessment of large-scale CSA interventions, but widely overlooked so far. Here we employ the example of two key components of climate-smart systems, that is, (a) agricultural yields and (b) carbon sequestration in agricultural soils, to raise awareness for the importance of the spatial dimension. We acknowledge that CSA is not bound to a certain agricultural practice and comprises several dimensions beyond agricultural productivity and carbon sequestration. However, in addressing the interlinked challenges of food security and climate change, these are key indicators that are widely assessed (e.g., Griscom et al., 2017; Smith et al., 2013; Tilman et al., 2011). To support our arguments, we illustrate the spatially variable effects of a hypothetical large-scale adoption of conservation agriculture (CA) in sub-Saharan Africa on yields and soil carbon sequestration. We employ CA as one example for a specific climate-smart agricultural management strategy for illustrative purposes, but do not equate CA with the concept of CSA. From the results of this illustrative analysis we identify main challenges that need to be addressed in the operationalization of CSA as a key strategy to meet global climate and food security goals.

2 | WHY LOCATION AND SCALE MATTER

2.1 | From where to go: The importance of initial conditions

Humans have altered their natural environment for millennia to grow crops, raise livestock, and harvest wood for different purposes. These interventions have been not globally uniform, but vary with respect to starting time, duration, and intensity of use (Ellis et al., 2013), leading to a distinct spatial pattern of human impact on the environment (Haberl et al., 2007).

Agricultural soils, therefore, experienced different structural and chemical changes compared to their natural state depending on this history of cultivation (Lal, 2018). Meta-analyses reported average soil organic carbon (SOC) losses of 30%–50% following cultivation, depending on land conversion type, climate zone, and moisture regime (Don, Schumacher, & Freibauer, 2011; Guo & Gifford, 2002; Ogle, Breidt, & Paustian, 2005). A recent modeling study, based on a large database of soil profile observations, emphasized the spatial variability of historical SOC losses, showing a much more nuanced spatial pattern of SOC losses (Sanderman, Hengl, & Fiske, 2017). Consequently, the potential carbon sequestration capacity at a location is strongly dependent on the past changes in soil characteristics due to cultivation (Lal, 2004). The actual present-day SOC content at a certain location influences the rate and duration of carbon sequestration rates after a management change (e.g., the conversion to no-till systems; West & Six, 2007), determining for which time period a soil can act as a carbon sink. Soils with larger depletion of SOC stocks may therefore provide a much higher capacity to store carbon than soils with smaller overall SOC losses (Figure 1a).

Similarly, present-day yields are spatially heterogeneous. Mostly differences in technological opportunities and management strategies (e.g., the application of fertilizers or irrigation) determine the yield that is currently achieved within a certain region (Lobell, Cassman, & Field, 2009). Studies of global yield gaps (=difference between observed yields and attainable yields given biophysical conditions and optimal management) showed great variations across the globe, with a clear distinction between regions with yield gaps almost closed (e.g., Western Europe and North America) and regions with on average high potentials to increase yields (e.g., sub-Saharan Africa) (Mueller et al., 2012; Neumann, Verburg, Stehfest, & Müller, 2010). However, also within these regions small-scale variations are remarkable. Consequently, potential gains in local agricultural production through intensification measures vary distinctly and depend

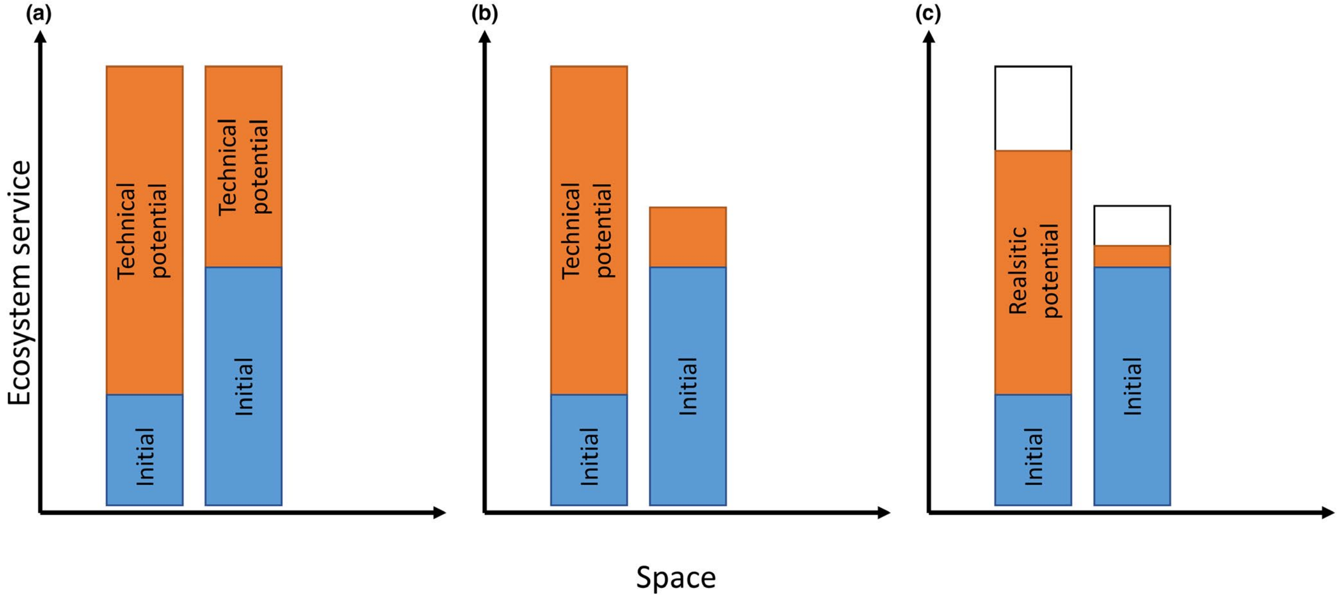

FIGURE 1 Determinants of potential carbon sequestration, yield or other ecosystem services upon adoption of climate-smart agriculture. Variability in initial conditions (a), variability in maximum potentials (b), and variability in socioeconomic constraints (c)

on the currently achieved yields. Regions with large yield gaps may achieve strong yield gains following the adoption of climate-smart practices (Pretty, 2008). This is, however, mainly because any improvement in the agricultural production process will increase yields, while it is unknown if equal yield levels can be obtained with sustainable practices as with conventional intensification. For example, field studies from areas with small yield gaps indicate that in the case of CA, the conversion to a climate-smart system leads, on average, to yield decreases (Pittelkow et al., 2015).

We acknowledge that the focus on yield gaps may underestimate the potential benefits of climate-smart practices, for example, on temporal stability of yields and adaptability to future climate conditions (Lipper et al., 2014). However, the yield response is an essential variable in a global context with expected increases in population and projected dietary developments. Lower yields from climate-smart practices would further increase the challenge for demand-side measures to limit these increasing demands (Davis et al., 2016).

2.2 | How far we can get (1): Maximum potentials determined by biophysical conditions

The carbon sequestration potential and yield increases are further determined by local variations of the resource base (e.g., soil, climate, water availability). The maximum capacity of a soil to store carbon is dependent on the soil's physical and chemical properties (Lal, 2018; Stewart, Paustian, Conant, Plante, & Six, 2007). For example, soils containing a high fraction of clay tend to have higher carbon saturation levels (West & Six, 2007). Furthermore, land degradation and erosion may have strongly limited the capacity of soils to sequester carbon as compared to their original conditions. Hence, even under the assumption of identical initial conditions (i.e., the same rate of SOC depletion due to cultivation) the absolute sequestration potential would vary greatly across space (Figure 1b).

Similarly, attainable yields, that is, the upper boundary which is biophysically possible, depend on soil and climatic conditions. Especially in the tropics, soil spatial variability can be large within small distances and substantially affect yields (Pittelkow et al., 2015; Richter & Babbar, 1991). Thus, yields under climate-smart management are analogous to yields under conventional intensification constrained at the local scale. Moreover, multiple case studies conducted under various environmental conditions have shown that the added value of particular climate-smart practices vary along environmental gradients. For example, CA tends to be more effective in arid regions due to improved water use efficiency (Soane et al., 2012), resulting in similar or even higher yields as compared to traditional tillage-based agriculture (Pittelkow et al., 2015). In contrast, decreasing yields have been reported in humid climates related to waterlogging of soils (Ogle, Swan, & Paustian, 2012). Hence, some practices considered as climate-smart might be a useful strategy for intensification under certain conditions, but can lead to substantial yield losses at other locations.

2.3 | How far we can get (2): Realistic potentials determined by socioeconomic barriers

Despite the purely biophysical limitations, also the local socioeconomic context is critical for the success and extent of the adoption of climate-smart practices. While agricultural regions that are well connected to the market and integrated in the global trade system generally provide higher opportunities to adopt technical advances and new approaches in agriculture, others are constrained by societal structures, institutional barriers, or unrewarding agricultural policies (Adenle, Azadi, & Arbiol, 2015). Under these circumstances it becomes difficult to reach adoption of climate-smart practices across larger scales. For example, the limited duration and constrained financial opportunities of extension programs promoting the introduction of CA restrict its long-term success in sub-Saharan Africa (Giller, Witter, Corbeels, & Tittonell, 2009). Therefore, benefits such as carbon sequestration and increased yields not only depend on what is biophysically possible and desirable at a particular location, but also on the socioeconomic context that may facilitate or constrain possibilities to upscale climate-smart practices to larger areas (Figure 1c; Brown, Nuberg, & Llewellyn, 2018).

2.4 | Feedbacks across scales

In sum, the spatial variability of initial conditions and the natural resource base, as well as the capability of local communities to adopt climate-smart management determines the aggregated carbon sequestration and production potentials. Accounting for the local context when assessing the opportunities of a climate-smart management is thus crucial. Untargeted claims to introduce a particular climate-smart practice at any place may lead to overall detrimental impacts at the larger scale. For example, if yield improvements are smaller than that with conventional intensification, cropland expansion may be triggered elsewhere to compensate for the losses (Lambin & Meyfroidt, 2011). Such compensation, of course, assumes constant market and consumer demand, which in turn depends on the scale of production changes and price elasticity. Similarly, carbon sequestration rates might be very small and not cost-effective at certain places (Smith, 2018). Using such land for climate-smart management might be not reasonable if under conventional intensification higher yields are feasible. A land sparing strategy that aims at minimizing additional carbon loss through deforestation and sparing land for afforestation might be much more beneficial than the small increases in soil carbon upon converting cropland to climate-smart systems. To date, global assessments often do not depict such nuances. For example, average CO_2 mitigation potentials are commonly applied to all cropland soils to calculate global mitigation potentials of improved soil management (Griscom et al., 2017; Smith et al., 2008). Such calculations do not account for the various aspects of spatial variability discussed above and potentially overestimate the carbon benefits of climate-smart management across scales. To distinguish the locations where benefits can be maximized from those where trade-offs are expected to dominate remains a critical issue to better estimate the potential of several climate-smart practices and target areas for implementation.

3 | ILLUSTRATION: SYNERGIES AND TRADE-OFFS OF LARGE-SCALE UPTAKE OF CA

3.1 | Accounting for spatially explicit variability

Using the example of a hypothetical, large-scale adoption of CA in sub-Saharan Africa we illustrate potential synergies and trade-offs that may be associated with climate-smart practices. We here concentrate on the effects of carbon sequestration in soils and changes to yields, as discussed in the previous sections. We base our illustrative example on methods and data published in the literature. While some of the assumptions are rather simple, they are all based on previous work. The analysis provides insight in our current knowledge in this field and into an approach for accounting for spatial variation in the assessment of the potential of climate-smart measures. We note that CA is only one instance of climate-smart management and results for other practices and indicators may differ in extent and spatial location.

To account for socioeconomic limitations to the uptake of CA in sub-Saharan Africa, we restrict the assessment to only the area available for future adoption of CA estimated in Prestele, Hirsch, Davin, Seneviratne, and Verburg, (2018).

Impacts on crop yields are approximated by applying crop-specific yield changes upon CA adoption (Pittelkow et al., 2015) to yield distribution maps for around the year 2000 (Monfreda, Ramankutty, & Foley, 2008). For crops not covered in Pittelkow et al. (2015) we assumed no impact of CA on yields. Yield changes were further differentiated by climate (arid vs. humid regions; Trabucco & Zomer, 2009) and irrigated or rainfed conditions (Siebert et al., 2015).

The carbon sequestration potential in CA soils was estimated following the methodology of Zomer, Bossio, Sommer, and Verchot (2017), who mapped the carbon sequestration potential in agricultural soils using scenarios from Sommer and Bossio (2014) and present-day soil carbon contents from Hengl et al. (2017). We constrain the sequestration potential by the historical SOC loss due to land-use change (Sanderman et al., 2017), that is, we assume that SOC content in CA soils cannot exceed natural levels (Figure S1). This is a rather optimistic assumption as it is unlikely that on agricultural land similar carbon levels can be reached as under natural vegetation (Lal, 2004).

Both yield changes and carbon sequestration were mapped at a continuous scale for each 5 arcminute grid cell over sub-Saharan Africa and classified into low, medium, and high impacts based on the lower quartile, interquartile range, and upper quartile, respectively (Figure 2c). Methodological details are given in Supporting Information S1–S4.

3.2 | Spatially variable impacts of CA adoption

Accounting for the barriers to CA adoption following the bottom-up scenario of Prestele et al. (2018) limits the potential CA area from 194 Mha (=all arable land) to 103 Mha (Figure 2a). While we base this estimate on frequently used land-use and cropland maps, the use of alternative maps could affect this estimate by up to 17%, corresponding to around 18 Mha. Scaled by the total cropland area in a product, the deviations are within around 3% (Table S3). Impacts on grid-cell level yields range from a decrease of 20.3% to an increase of 5.8%. CA adoption may lead to substantial yield declines in the south of Angola, the coastal region of western Africa, and Madagascar

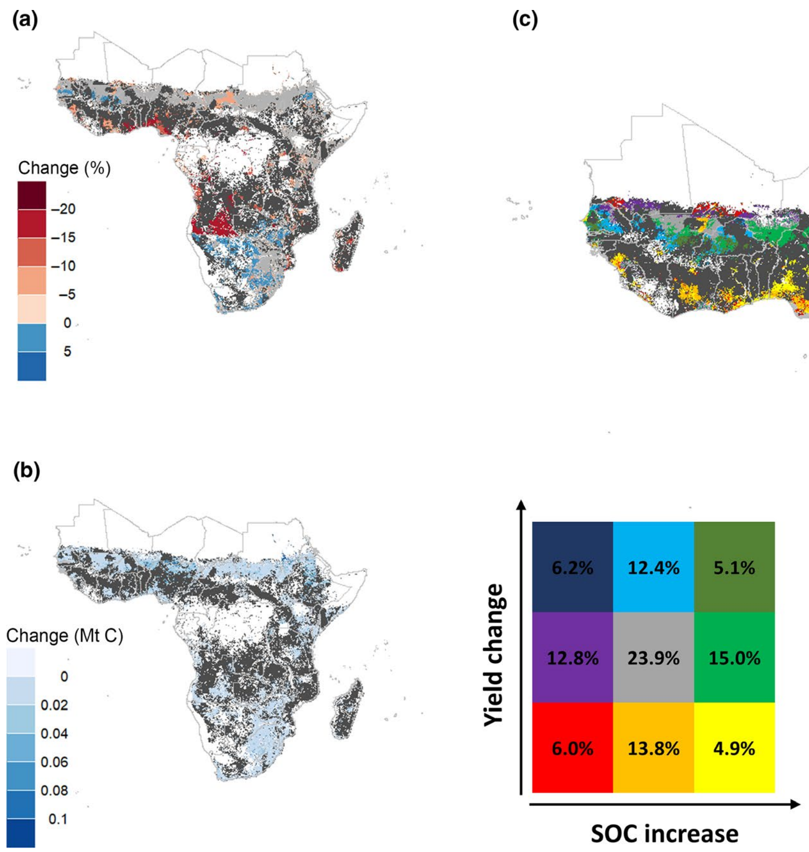

FIGURE 2 Yield changes relative to present-day conditions (a) and carbon increases in Mt C per 5 × 5 arcminute grid cell (b) following the implementation of conservation agriculture. Synergies and trade-offs (c) concerning the two indicators based on quantile classification. The percentages in the legend box indicate the share of pixels falling into each category. Light gray areas in (a) indicate no changes to yields due to missing data. Dark gray areas indicate croplands that are not suitable for conservation agriculture according to the potential map of Prestele et al. (2018)

(Figure 2a). These are mainly the regions where root crops are the dominant crops, which have been reported to respond with substantial yield decreases under CA (Pittelkow et al., 2015). Small yield increases at the grid-cell level are found for the southern part of Africa (Botswana, South Africa, Zambia, Zimbabwe). However, these areas are also most uncertain as a substantial part of agricultural production (~70%) is based on crops that are not covered by Pittelkow et al. (2015) and, hence, yield impacts are unknown.

The highest gains in soil carbon stocks occur at the northern edge of cropland extent in sub-Saharan Africa, with some smaller high-potential areas in South Africa, Kenya, and Tanzania (Figure 2b). Compared to present-day carbon stocks the changes range from small (~0.5%) to almost threefold increases (~173%) at the grid-cell level, which results in increases between 1.0 and 13.0 t/ha. If accounted for the actual area under CA within a grid cell, the maximum potential found is around 0.1 Mt C.

Figure 2c identifies potential trade-offs and synergies between agricultural production and carbon sequestration under CA management. Given the assumptions in our analysis, the highest opportunities to gain in both dimensions (dark green, 5.1% of CA adoption area) or accept weak trade-offs (light green, 15.0%; light blue, 12.4%) are found in South Africa and in the Sahel. In contrast, climate-smart management in the form of CA leads to only small carbon increases at the cost of strong yield losses (red, 6.0%) in the southeast of Angola and various smaller regions across sub-Saharan Africa. A trade-off between carbon sequestration and agricultural production occurs in regions colored in yellow (4.9%) and orange (13.8%; e.g., the coastal region of Western Africa), where carbon gains could be achieved only on the cost of strong yield losses. Almost a quarter (23.9%) of the potential CA area would be subject to weak yield losses and medium carbon gains (gray).

These results emphasize the very heterogeneous pattern of potential synergies and trade-offs of CA implementation across sub-Saharan Africa, highlighting the importance of the spatial dimension in such calculations.

3.3 | Potential feedbacks to the continental scale

The spatial heterogeneity of impacts may have implications at the larger scale, for example by a larger demand for agricultural areas, and associated deforestation, in response to yield losses. To provide an indication of these effects, we calculated the total agricultural production and overall carbon sequestration under the CA adoption scenario based on the spatially explicit results discussed in the previous section (Supporting Information S5). Changes in agricultural production are expressed relative to present-day numbers, assuming that the relative yield changes applied to the individual crops represent the differences in yield between sustainable and conventional intensification. We use this as a first approximation, as most of the field studies underlying the meta-analysis of Pittelkow et al. (2015) originate from regions with small yield gaps.

Given these assumptions, the large-scale implementation of CA would lead to a decrease of production by about 2.6% as compared to conventional intensification, while around 0.47 Gt carbon could be sequestered. If the decrease in production would be compensated for by cropland expansion, carbon losses from land-use change elsewhere are unavoidable. Assuming average present-day yields on new cropland areas, an expansion of cropland into the most suitable areas following Zabel, Putzenlechner, and Mauser (2014), and present-day carbon stocks according to West et al. (2010) and Sanderman et al. (2017), the carbon loss from cropland expansion adds up to ~0.44 Gt C (Supporting Information S6). Thus, the carbon loss is in the same order of magnitude than what has been gained by CA management. In reality the losses may be even larger, as cropland is likely to expand in areas less suitable for agricultural production, resulting in lower yields as the current average and, therefore, larger areas of land-use conversion.

3.4 | Limitations of the illustration

We acknowledge that our calculations use simplified assumptions. Many of the underlying data are uncertain and more research is required to reduce these uncertainties. For example, the cropland mask underlying our analysis based on Ramankutty, Evan, Monfreda, and Foley (2008) may underestimate the total cropland area in sub-Saharan Africa. Similarly, the crop-type maps of Monfreda et al. (2008) do not necessarily depict the present-day crop-type distribution as they are based on the year 2000. However, we used these datasets to ensure consistency across the different datasets required for our analysis. Currently available spatial data also do not allow capturing the full extent of spatial variation in yield impacts and carbon sequestration potential. Moreover, with uptake of CA farmers may adopt crop choice to avoid potential yield declines. However, rather than a precise quantification, the purpose of the analysis is to raise awareness for potential detrimental consequences of untargeted implementation of climate-smart practices. Thus, we made assumptions that lead to the most favorable outcomes of CA and the results indicate an upper potential of CA implementation, but are still rather disappointing on the carbon sequestration potential. Furthermore, CA is used here as only one example of a practice considered to be climate smart. The synergies and trade-offs depicted in our illustration may be very different if other practices and indicators are assessed. However, while the location and quantities of trade-offs may differ, the spatial variability remains an important issue not yet sufficiently accounted for in large-scale assessments.

Conservation agriculture and other climate-smart systems may also have benefits beyond the effects on yield and carbon sequestration. In some cases, adoption may be justified even in case of negative implications on the dimensions analyzed here because of favorable impacts on, for example, household income, water savings, or yield stability (Palm, Blanco-Canqui, DeClerck, Gatere, & Grace, 2014). Extending our approach to additional practices, a wider set of ecosystem services and livelihood conditions is likely to be more successful than a dogmatic approach neglecting potential trade-offs. Our illustrative analysis substantiates the concerns raised in the sideline of many papers on the local consequences of the adoption of climate-smart management.

4 | FROM GLOBAL CLAIMS TO SPATIALLY EXPLICIT TRADE-OFF ANALYSIS

The concepts of SI and CSA already have a history of ~20 or ~10 years, respectively (FAO, 2010; Pretty, 1997), but gained momentum in the literature recently as a solution for navigating trade-offs between the interlinked challenges of food security and climate change mitigation (e.g., Smith, 2018; Weltin et al., 2018). Some authors mainly base the concepts on increasing production while minimizing environmental costs in the context of food security (Godfray & Garnett, 2014; Pretty, 2008); others define absolute sustainability criteria within planetary boundaries (Rockström et al., 2017) or focus on imitating ecological processes in agriculture (Kuyper & Struik, 2014; Tilman, 1999). However, we argue that independent of definitional nuances these approaches are, in the literature, often centered too much on a global perspective and optimal outcomes of various SI or CSA measures, while overlooking the spatial variability of trade-offs and synergies. While the context-specificity is a core component of the CSA concept (e.g., Bell et al., 2018; Lipper et al., 2014), it is often neglected in the context of global potentials of climate-smart practices on contributing to food security and climate change mitigation goals. The overall benefits could be maximized, if the implementation is targeted toward the areas where yield losses are negligible and gains in other ecosystem services are largest. This requires, however, also a consideration of the potential for adopting these measures given the socioeconomic context and the institutional and financial support available in the area. CSA, by definition, includes efforts at multiple administrative levels to actually turn promising technologies into site-specific climate-smart systems (Lipper et al., 2014). In contrast, land sparing through maximizing yields by means of conventional intensification in areas with small carbon gains can free up land for restoration and afforestation to, for example, increase the overall carbon sink capacity. At the same time, the many positive impacts of SI or CSA could outweigh the potential yield losses as compared to conventional intensification through long-term benefits and may be chosen for in combination with efforts toward sustainable consumption.

Management techniques that have been proposed to be climate-smart need to be rigorously evaluated at the local scale prior to promoting them at a global scale. To date, the lack of suitable indicators and data largely limit comprehensive and spatially explicit approaches. Future approaches should therefore focus on (Figure 3):

1. Identification of a range of most promising climate-smart interventions and relevant indicators. Recent literature review and meta-analyses provide entry points (Mahon, Crute, Simmons, & Islam, 2017; Scherer et al., 2018; Weltin et al., 2018). Priority should be given to the question: "Which agricultural systems are sustainable and climate smart at which location?"
2. Mapping of the spatially variable initial conditions of relevant ecosystem services to determine the starting point for CSA interventions at the local scale ("What is the current status of depletion?"). Spatial analysis, integration of various data streams, and modeling approaches need to be employed. For example, statistical models can be used to extend in situ measurements across larger scales (Hengl et al., 2017; Sanderman et al., 2017). Due to inherent uncertainties from such approaches, robust uncertainty estimates are a crucial part of this step.
3. Mapping of the spatially variable maximum (=biophysically possible) and realistic (=constrained by socioeconomic conditions) potentials in order to maximize relevant ecosystem services while not depleting others, including expected changes under future climatic conditions. The required methods correspond to approaches for the mapping of initial conditions, with a stronger focus on modeling approaches (e.g., crop models in terms of agricultural yields; vegetation models for carbon sequestration estimates). Deriving realistic potentials includes the most critical

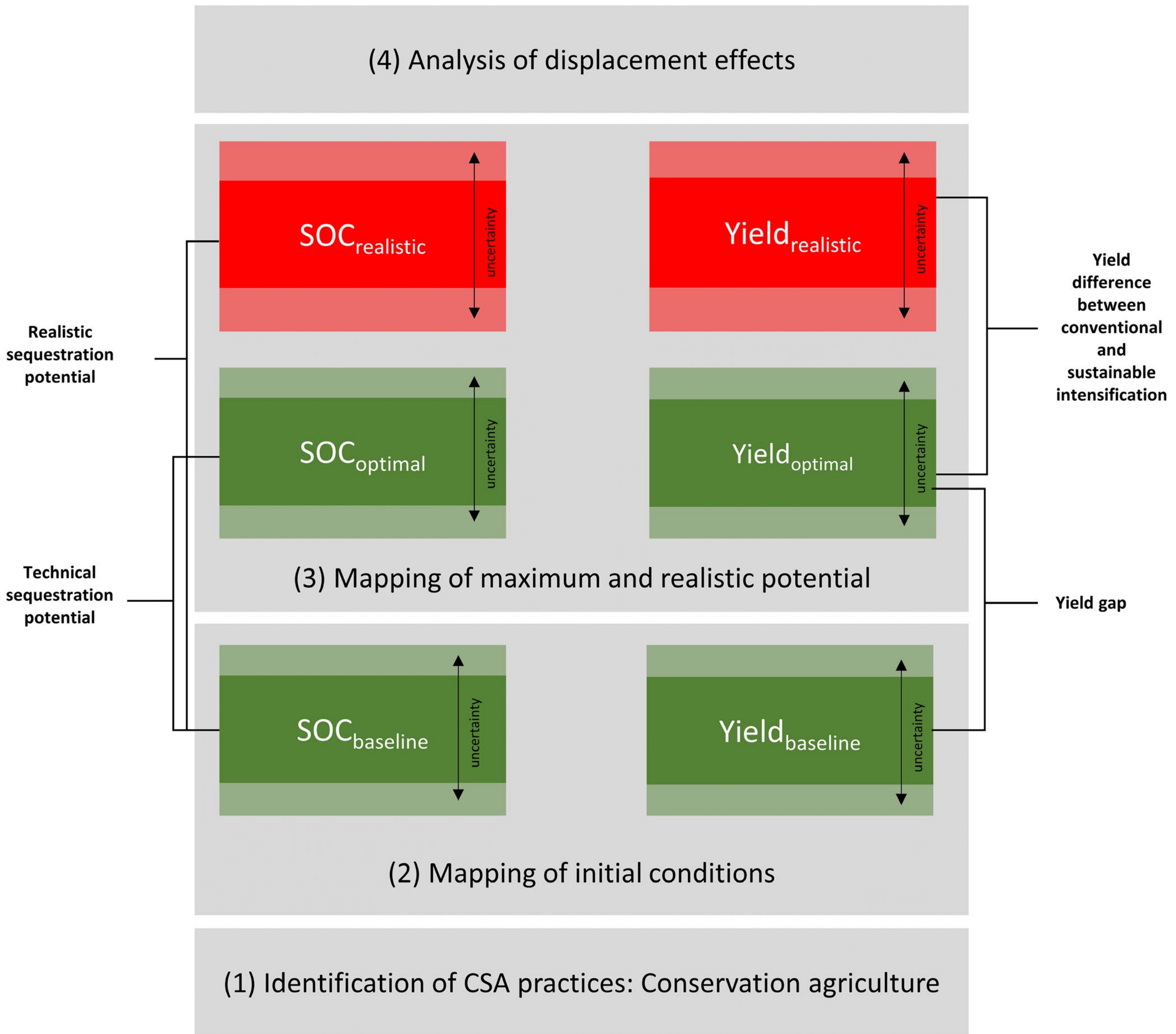

FIGURE 3 Schematic overview of spatially explicit trade-off analysis required to evaluate climate-smart agriculture (CSA) practices from the local to continental (global) scales, based on the example of conservation agriculture and for yield and carbon impacts. SOC, soil organic carbon

step as multiple biophysical and socioeconomic drivers will determine these potentials, but large knowledge gaps exist especially regarding socioeconomic constraints.

4. Analysis of the risk and extent of displacement effects in case yield differences occur in consequence of the adoption of climate-smart management. Such analyses require more knowledge on the linkages between demand and supply and the ways in which CSA could also contribute to limiting demand (Scherer & Verburg, 2017).

5 | CONCLUSIONS

A large body of research suggests that SI and CSA can contribute to the interlinked global challenges of food security and climate change. However, this potential is strongly reduced if spatial variation is ignored and untargeted implementation may cause unfavorable feedback effects. Calculating potentials based on average numbers has the risk of obscuring many of the trade-offs at the local scale and hampers the achievement of global targets rather than supporting them. Relying on unnuanced estimates of large potential contributions from climate-smart practices can risk inefficient policy investments by governments that fail to deliver on food security and climate mitigation goals across scales. Expectations of CO_2 savings from climate-smart technologies are very high. However, basing climate policies on aggregated estimates may risk delays in achieving emissions reduction goals for particular regions. To really operationalize the SI and CSA concepts, and maximize synergies, the identification and prioritization of “win–win” locations (i.e., those areas where benefits are largest and trade-offs are minimized) requires special attention both in science and policy.

Sustainable intensification and CSA can involve a large range of agricultural practices that need to be locally adapted. At some places conventional intensification may be included if the global benefits prevail the local impacts. Moreover, potential displacement effects need to be considered and strongly depend on the yield responses to adopting CSA measures. If yield is negatively affected as compared to conventional intensification, there is a high risk of displacement of production to other regions, with high potential of associated losses in ecosystem services that may offset the gains from CSA. Promoting the synchronization of supply- and demand-side CSA measures to fully use the potentials is a promising option beyond purely supply-side approaches.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed.

ORCID

Reinhard Prestele https://orcid.org/0000-0003-4179-6204
Peter H. Verburg https://orcid.org/0000-0002-6977-7104

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

Supinfo

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